WHY EVERY BIPOLAR PLANETARY NEBULA IS 'UNIQUE'

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ABSTRACT

We present the many evolutionary routes that progenitors of bipolar planetary nebulae (BPNe) can take. Overall, there are about a hundred qualitatively different evolutionary routes, hence about a hundred qualitatively different types of BPNe. Within each type there are quantitative differences as well. Adding the dependence of the appearance on inclination, we find that the number of different apparent structures of BPN is about equal to, or even larger than the number of known BPNe and proto-BPNe. Accordingly we argue that every BPN is a 'unique' object in its appearance, but all can be explained within the binary model paradigm. Therefore, we request a stop to the attaching of adjectives such as 'unique', 'peculiar', and 'unusual' to BPNe and proto-BPNe, thereby removing the need to invoke a new model for almost every 'unusual' BPN. As a case study we try to build a binary model for the proto-BPN OH231.8+4.2. In our preferred model the AGB Mira-type star has a main sequence companion of mass $\sim 1 M_\odot$, orbital period of ~ 5 yr, and eccentricity of $\gtrsim 0.1$.

Key words: planetary nebulae: general − stars: individual (OH 231.8+4.2) − stars: binaries: close − stars: AGB and post-AGB − stars: mass loss

1. INTRODUCTION

With more sensitive observations in recent years a trend has arisen of attaching adjectives such as 'peculiar' (e.g., Lopez *et al.* 2000 to the PN KjPn 8) and 'unique' (e.g., Bourke *et al.* 2000 to the Frosty Leo Nebula [IAS 09371+1212]) to bipolar planetary nebulae (BPNe) and proto-BPNe. In many cases such adjectives are followed by a claim that a new theory is required to explain the formation of such 'peculiar' and 'unique' BPNe (e.g., Trammell 2000 for the PN AFGL 618). BPNe are defined as axially symmetric PNe having two lobes with an equatorial waist between them. In the present paper BPNe stand both for BPNe and proto-BPNe. The goal is simply to show that in the binary model for the formation of BPNe there are more than a hundred different evolutionary routes to form BPNe, hence every BPN is 'unique', and there is no need to invoke new evolutionary paradigm for each one.

The observations that other types of binary systems can form bipolar structures and/or blow jets set the binary model for the formation of BPNe on solid ground. Such systems are symbiotic nebulae (e.g., Morris 1990; Corradi & Schwarz 1995; Corradi *et al.* 2000), supersoft X-ray sources (Southwell *et al.* 1996; Southwell, Livio, & Pringle 1997; Becker *et al.* 1998; Motch 1998; Lee & Park 1999) and the central binary system of the BPN NGC 2346 (Bond & Livio 1990). On the theoretical side, Soker & Rappaport (2000; hereafter SR00) show by performing population synthesis simulations that binary systems can account for the fraction of BPNe among all PNe. By achieving its goal, the present paper will strengthen the binary model for the formation of BPNe.

Before listing the different evolutionary routes in section 3, we take the proto-BPN OH 231.8+4.2 (hereafter OH231; also termed OH 0739−14) as a case study. This is a well studied proto-BPN (e.g., Cohen *et al.* 1985; Kastner *et al.* 1992, 1998; Kastner & Weintraub 1995; Alcolea *et al.* 2001, hereafter ABSNZ; Bujarrabal *et al.* 2001, hereafter BCAS). ABSNZ raised to question all existing models for the formation of OH231. In particular, ABSNZ argue that it is hard to explain the large momentum of the outflowing gas in the lobes by existing theories. BCAS, in an excellent thorough study of proto-BPNe, extend the problem of the momentum source to other objects. Disagreeing with the view of ABSNZ and BCAS that existing theories cannot account for the large momentum in the lobes, I argue in section 2 that binary models can naturally account for the large momentum fluxes observed in BPNe (and proto-BPNe), in addition to the natural explanation of the bipolar structure. Cohen *et al.* (1985) already suggested that the bipolar structure is due to a binary companion to the Mira variable, which they claimed to have detected, and they further pointed to the connection of this system to symbiotic stars. Section 4 contains a short summary.

2. A CASE STUDY: OH231.8+4.2

2.1. Observed Properties of OH231

The purpose of this section is to show that the proto-BPN OH231 can be naturally explained by a binary model, as was suggested already by Cohen *et al.* (1985), despite the claims of ABSNZ and BCAS that there is no satisfactory theory to account for this and similar BPNe. Some of the scenarios studied here will be used in the next section for building a general scheme of models.

To build a binary model for OH231 we use the following properties (ABSNZ; BCAS). (1) A mira variable is the mass-losing star (primary), with the companion luminosity limited to be $L_2 < 10^3 L_\odot$. The limit is deduced from the 'nice' Mira-type pulsations seen in reflection (Kastner *et al.* 1992; J. Kastner 2001, private communication). (2) The equatorial mass in the bipolar nebula is not much larger than the mass in the lobes. This basically implies that the bipolar flow cannot be formed through confinement by a dense equatorial matter. (3) The sum of the absolute values of the momentum in the lobes is $p \simeq 27 M_\odot$ km s^{-1}. (4) Total kinetic energy of the expanding nebula is $E_k \simeq 1700 M_\odot$ km^{-1} s^{-1}. (5) Expansion velocities of up to 430 km s^{-1} are measured. (6) The nebula contains no, or a very small mass of, photoionized gas. (7) An increase by a factor of ~ 100 occurred in the mass-loss rate ~ 4500 yr ago. (8) The high momentum flow started ~ 800 yr ago. (9) The acceleration phase of the high momentum flow lasted a short time (relative to its 800 yr of age). (10) Presently the mass-loss rate by the AGB star is $\sim 2 \times 10^{-4} M_\odot$ yr^{-1}. (11) The lobes are not inflated. There are two basic interactions types between fast and slow flows in PNe: adiabatic (also termed energy conserving) and radiative (momentum conserving). In the adiabatic case the shocked fast wind cooling time is much longer than the flow time, while in the radiative case energy is lost via radiation by the cooling shocked gas. BCAS ruled out the adiabatic case for OH231, mainly on the ground of the shape of the lobes, which are not inflated as is expected in the adiabatic flow.

2.2. Models with a WD Companion

2.2.1. A compact WD companion

An adiabatic flow requires low density and fast CFW (collimated fast wind blown by the companion), most likely a CFW blown by a WD companion at velocities of $v_c \simeq 5000$ km s^{-1}. To supply most of the kinetic energy cited above in $\tau = 800$ yr the mass-loss rate from the WD companion into the CFW should be

$$\dot{M}_c = 2 \times 10^{-7} \left(\frac{E_k}{10^3 M_\odot \text{ km}^2 \text{ s}^{-2}} \right) \left(\frac{\tau}{500 \text{ yr}} \right)^{-1} \left(\frac{v_c}{5000 \text{ km s}^{-1}} \right)^{-2} M_\odot \text{ yr}^{-1}. \tag{1}$$

However, there is a problem with this idea. To blow a wind at such a rate the WD must accrete at a rate several times higher, $\dot{M}_{\rm WD} \sim 10^{-6} M_\odot$ yr^{-1}. A WD accreting at such a rate has a steady nuclear burning (e.g., Fujimoto 1982) and swells to a radius of $R_{\rm WD} \gtrsim 0.1 R_\odot$ (Hachisu, Kato, & Nomoto 1999). The escape velocity from the extended wide dwarf surface decreases to 2300 km s^{-1} for a $1.3 M_\odot$ WD, with much lower values for lighter WDs. This reduces the CFW speed, hence increases the required mass-loss rate by a factor of > 4 compared with that given in equation (1). This implies even a higher accretion rate and a larger radius of the swollen WD, with escape and CFW velocities of $v_c \lesssim 1000$ km s^{-1}. From equation (1) the required mass-loss rate into the CFW for this lower speed is $\sim 10^{-5} M_\odot$ yr^{-1}. At such high accretion rates the WD has swollen to a radius of $\gtrsim 0.5 R_\odot$. The problem with this model is the elongated shape of the nebula, which means there is no massive gas to confine the pressure-accelerated gas to the polar direction (BCAS). This reduces the efficiency of the energy momentum interaction, such that a much higher mass-loss rate into the CFW is required. In such a case we are in the regime of momentum-conserving interaction.

2.2.2. A Swollen WD companion

We now examine the case of a CFW from a swollen WD, such that the interaction is momentum conserving. The required momentum constrains the mass-loss rate to

$$\dot{M}_c \gtrsim 10^{-4} \left(\frac{p}{25 M_\odot \text{ km s}^{-1}} \right) \left(\frac{\tau}{500 \text{ yr}} \right)^{-1} \left(\frac{v_c}{500 \text{ km s}^{-1}} \right)^{-1} M_\odot \text{ yr}^{-1}. \tag{2}$$

We note that at very high accretion rates a WD companion will not ionize the nebula, since it has an extended photosphere with effective temperature of $\lesssim 3 \times 10^4$ K. The required accretion rate for that to occur is $\dot{M}_{\rm WD} = 6 \times 10^{-6} M_\odot$ yr^{-1} for $M_{\rm WD} = 0.6 M_\odot$ and $\dot{M}_{\rm WD} = 4 \times 10^{-5} M_\odot$ yr^{-1} for $M_{\rm WD} = 1.3 M_\odot$ (Hachisu et $al.$ 1999). Therefore, the WD in the momentum-conserving case does not ionize the circumbinary material (unless the WD is extremely massive and the accretion rate is fine-tuned).

The luminosity of an accreting WD due to nuclear burning is $L > 10^4$ K. There are no observational indications for such a luminous companion. Therefore, in order for this model to work the mass accretion rate has to be below the steady nuclear burning rate. This rate is $10^{-7} M_\odot$ yr^{-1} for a $1 M_\odot$ WD, increasing with WD mass (Fujimoto 1982). Too massive WD means recurrent outbursts on short time scales (Fujimoto 1982), and for too light WDs the mass accretion rate should be even smaller. Under what circumstances can the accretion rate from an AGB star drop by ~ 3 orders of magnitude in $\lesssim 300$ years? There are two possibilities. The first is after a Helium flash (thermal pulse) and the second is a termination of a Roche lobe over flow (RLOF). The mass-loss rate by an AGB star increases somewhat for a short time after the thermal pulse, and then decreases by two orders of magnitude (Blöcker 1995). The decease in stellar radius after the thermal pulse may lead to a higher wind velocity, further reducing the accretion rate. The

RLOF process is unstable in WD-AGB binary systems since the AGB star at the beginning of the mass-loss process is more massive than the WD; this case may be applicable to a main sequence companion, as discussed below. We conclude that a swollen-WD companion model can explain the properties of OH231, but only if the WD mass accretion rate is fine-tuned, such that it drops by $\gtrsim 3$ orders of magnitude in $\lesssim 300$ years, so presently the WD is back to its normal size and has no nuclear burning on its surface. This is in contradiction with the finding of ABSNZ that the high mass-loss rate typical of late AGB phases is still going on. Another way to "hide" a WD, swollen or not, is inside the AGB envelope, i.e., a common envelope system. However, it is questionable whether an AGB star harboring a WD inside its envelope, or a WD that has collided with its core, will behave like a normal pulsating AGB star, as OH231 does.

Although unlikely to be the case in OH231, the process in which a close WD companion swells to a radius of $\sim 0.1 - 10 R_\odot$ by accreting at a very high rate from an AGB star can form very interesting BPNe. When the mass-loss rate by the primary decreases toward the post-AGB phase in these systems, the WD shrinks and its temperature rises to the point where it starts ionizing the nebula, forming a symbiotic nebula on its way to becoming a PNe.

2.3. A Main Sequence Companion

We are left with a CFW blown by an accreting main sequence companion, for which the CFW speed is ~ 500 km s^{-1} and the momentum-conserving case applies. The required momentum constrains the mass-loss rate according to equation (2). To blow such a wind, the main sequence star, which unlike a WD has no surface nuclear-burning energy source, must accrete at a rate higher by a factor of $5-10$ than its mass-loss rate to the CFW. The total mass blown to the nebula of OH231 at a speed of $v_c = 500$ km s^{-1} is $M_c = 0.05(p/25 M_\odot$ km s$^{-1})M_\odot$. During that period the companion has accreted a mass of $0.25 - 0.5 M_\odot$ at an average accretion rate of $\dot{M}_2 = 0.5 - 1 \times 10^{-3} M_\odot$ yr^{-1}. However, it seems that the acceleration phase lasted a short time (ABSNZ), hence the accretion rate was higher. If lasting 250 years, the mass accretion rate is $\dot{M}_2 \simeq 1 - 2 \times 10^{-3} M_\odot$ yr^{-1}, which requires the system to go through a RLOF. From the calculations of Prialnik & Livio (1985) it seems that a companion of $M_2 \sim 1 M_\odot$ with its outer convective envelope can accrete such a mass in ~ 250 yrs, even if not thermally relaxed. Although Prialnik & Livio (1985) study the accretion onto a fully convective $0.2 M_\odot$ main sequence star, their calculations show that stars can accrete at very high rates.

The accretion (from a disk) luminosity is

$$L_{\mathrm{acc}} = 3 \times 10^4 \left(\frac{M_2}{M_\odot} \right) \left(\frac{\dot{M}_2}{2 \times 10^{-3} M_\odot \text{ yr}^{-1}} \right) \left(\frac{R}{R_\odot} \right)^{-1} L_\odot. \tag{3}$$

Some fraction of this energy goes to accelerate the CFW, so the radiative luminosity will be somewhat lower. There is no accurate upper limit on the luminosity of a possible companion, but it is

$L_2 < 1000L_\odot$. So the present luminosity must be lower than that during the high mass transfer rate phase. There are two possibilities.

(1) A decrease in mass-accretion rate. For a limit of $L_2 < 1000L_\odot$ on the companion's luminosity, the present mass-accretion rate is $\dot{M}_2 \lesssim 10^{-4}M_\odot$ yr^{-1}. Since the central AGB star loses mass at a rate of $\sim 2\times 10^{-4}M_\odot$ yr^{-1} (ABSNZ), the companion accretes only a fraction of that, and the limit is met. In this case the companion stays outside the AGB envelope. At the beginning of the mass transfer the stars had about equal masses, and the RLOF requires the orbital separation to be about twice the AGB radius, hence $a \simeq 4AU$, and the orbital period is ~ 5 yrs. The parameters of such a system are similar in many respects to those of the Red Rectangle, with one significant difference: in the proposed model for OH231 a large amount of gas was transferred from the AGB star to its companion, part of which was ejected in the CFW, while in the Red Rectangle only a small amount of gas was transferred. Namely, either the Red Rectangle avoided a RLOF (Waelkens *et al.* 1996), or else the RLOF occurs only after a substantial part of the AGB envelope has been removed (Van Winckel 2001). There are relatively many post-AGB binary systems with similar parameters to that of the Red Rectangle (Van Winckel 1999), in particular HD213985, which has a companion with a mass of $M_2 \simeq 2M_\odot$ (Van Winckel 1999). The companion has probably gained its mass by accretion (H. Van Winckel 2001, private communication). Like these systems, it is quite possible that the large mass transferred between the stars in OH231 increased the eccentricity (Soker 2000). Therefore, if this is the correct scenario for OH231, we predict that the central system is a binary system where there is a $1M_\odot$ main sequence companion to the AGB star, at an orbital period of ~ 5 years, and eccentricity of $e > 0.1$.

(2) Common envelope. Another way by which a companion can escape detection is a common envelope evolution. Since the AGB star shows regular pulsational behavior (Kastner *et al.* 1992) the companion can't be too massive, $M_2 < 0.5M_\odot$. The companion can exists inside the envelope, or it has collided with the core of the AGB star. The CFW which supplies most of the momentum of the nebula was blown during a short time, few$\times100$ years, before the companion entered the envelope. It is also plausible that during a collision between a star and the AGB core a disk is formed with two jets. The morphology of the BPN NGC 2346, with its 16-day orbital period binary (Bond & Livio 1990), shows that the bipolar morphology is not due to a collision.

To summarize, we propose the following model for the formation of the bipolar nebula of OH231. Due to the increase in the AGB stellar radius, possibly a fast increase after a thermal pulse, the system entered a strong tidal interaction phase ~ 4500 yr ago. This increased the mass-loss rate, and caused the orbit to shrink because of orbital angular momentum loss to the AGB envelope and wind. At the same time the radius of the AGB star further increased due to its mass-loss (Iben & Livio 1993) and evolution, and its mass decreased while the accreting main sequence companion stared to blow a weak CFW. Eventually the AGB star filled its Roche lobe, ~ 800 yr ago. It is quite plausible that the AGB star filled its Roche lobe only during the maximum radius phase during a pulsation cycle. For several hundred years the mass transfer rate was very high and the accreting main sequence companion blew a strong CFW, which supplied the momentum of the polar flow observed today. Next, either RLOF ended and mass-accretion rate decreased by

2 orders of magnitude while the companion stayed outside the AGB envelope, or the system went through a common envelope phase. In the first case the companion has a mass of $M_2 \gtrsim 1 M_\odot$ and the system is similar to the binary systems at the center of the Red Rectangle and other similar systems (Van Winckel 1999), while in the latter case the companion is lighter, $M_2 \lesssim 0.5 M_\odot$, hence the RLOF is unstable, and the present system may be similar to the one at the center of NGC 2346. Quantitative detailed study is required here after more observational constraints are available, e.g., limits on the luminosity of a companion, a limit or detection of AGB envelope rotation, and a limit or detection of nonradial pulsation modes, which may hint at a companion inside the envelope and/or rotation.

Finally, the companion to the AGB star can explain the departure of OH231 from axisymmetry (Soker & Hadar 2001 and references therein). The type of departure from axisymmetry is the 'bent' type according to the classification of Soker & Hadar (2001), i.e., the two lobes of OH231 are bent to the same side. This is most clearly seen in the polarization maps of Kastner & Weintraub (1995).

3. EVOLUTIONARY ROUTES

ABSNZ term OH231 a 'unique object'. Similar terms, e.g., 'peculiar object', are used in many papers discussing BPNe. We argue that most BPNe (including proto-PNe) are unique in the sense that the stellar binary model for the formation of BPNe has many qualitatively different evolutionary routes. The number of different evolutionary routes is about equal to the number of well resolved BPNe. Some routes are rare, and no known BPNe belong to them, some routes are common and they contain several known BPNe, and many routes have only one 'unique' known object belong to them. Even within an evolutionary channel, quantitative differences exist, e.g., the opening angle of the CFW (if narrow they are termed jets), which may cause BPNe to look 'unique'. Therefore, our view is that there is nothing unique about 'unique' BPNe in the frame of the stellar binary model for their formation. At present, however, with most bipolar PNe we cannot tell the routes which led to their formation; for this, gasdynamical simulations of the interaction between the slow AGB wind and the CFW blown by the companion are required on the theoretical side, while detection of companions in the center of bipolar PNe are required on the observational side.

The main physical parameters characterizing binary progenitors of BPNe are (a) orbital semi-major axis; (b) eccentricity; (c) the initial mass and evolution (e.g., helium flash at the end of the AGB) of the mass-losing star; (d) mass and type (main sequence or WD) of the companion. These parameters can lead to many qualitatively different types of evolution during the final stages of the AGB and post-AGB phases (and of course infinite quantitatively different evolutionary paths). The different evolutionary types are summarized in Table 1. The basic assumption is that most BPNe are formed by a CFW (collimated fast wind) blown by an accreting companion (Morris 1987;

SR00). The basic processes that determine the type of BPNe, which are summarized in Table 1, are:

(1) CFW type. The CFW (or jets) blown by the accreting companion can be either strong or weak relative to the slow wind blown by the mass-losing star, as defined in SR00. In eccentric orbits the CFW may be strong near periastron (when accretion rate is high) and weak (or not exist at all) near apastron (Soker 2001a).

(2) Type of companion and its response to accretion. The companion can be a main sequence star, when the initially more massive star is the present AGB star, or it can be a WD if the initially less massive star is the present AGB star (see SR00 for more details). The WD response to accretion depends on its mass and on accretion rate (e.g., Fujimoto 1982; Hachisu *et al.* 1999). We distinguish four main cases. For low accretion rates, but not too low, so that the WD still blows a CFW, there is no steady nuclear burning; instead the WD experiences a symbiotic nova type event, i.e., an outburst (e.g., Prialnik & Kovetz 1995). After the eruption the WD is hot and it enters a supersoft X-ray phase. The range of mass accretion rates for this process depends on the WD mass, but can be approximately taken to be $10^{-8} \lesssim \dot{M}_a \lesssim 10^{-7} M_\odot$. The descendant PN structure depends on whether or not an outburst occurs during the final few thousands years. For higher accretion rates, $\dot{M}_a \gtrsim 10^{-7} M_\odot \text{ yr}^{-1}$, there is a steady nuclear burning on the WD surface. For lower accretions rates in this range, $10^{-7} \lesssim \dot{M}_a \lesssim \text{few} \times 10^{-6} M_\odot$ (the exact range depends on the WD mass), the WD is a supersoft X-ray source. For very high accretion rates, $\dot{M}_a \gtrsim 10^{-5} M_\odot \text{ yr}^{-1}$, the WD swells substantially, up to several solar radii (Hachisu *et al.* 1999), and its surface temperature is $T_{\text{ph}} \lesssim 30,000$ K so that it stops ionizing the nebula around it, and the escape velocity decreases to several hundred km s^{-1}. The structure of the descendant PN depends on whether or not the WD ionizes the circumstellar medium. Of course, a wide range of the WD's wind properties exists within each of these possibilities, further enlarging the variety of descendant PN structures.

(3) Tidal interaction. Since tidal interaction, as manifested in the synchronization and circularization times, is very sensitive to the orbital separation, in most cases there is either a strong tidal interaction or negligible interaction. Strong interaction means for our purposes that there is a synchronization between the orbital period and the spin period of the AGB mass-losing star. This leads to a high equatorial mass-loss rate. When the two stars are close enough, the systems may enter a RLOF, or even a common envelope (Iben & Livio 1993).

(4) Precession. The CFW (or jets) blown by the companion may precess, leading to the formation of a point symmetric PN.

Some of the evolutionary routes apply to other types of systems, as indicated in the table. The connection of these systems, e.g., symbiotic systems and supersoft X-ray sources, to PNe were suggested many times in the past. We also note that in some cases some of the evolutionary routes will form elliptical PNe rather than BPNe, e.g., when both a weak tidal interaction and a weak CFW exist (Soker 2001a).

The numbers of the different possibilities in each one of these five parameters are listed in Table 1. If the processes were independent, there would be $3 \times 5 \times 4 \times 2 = 120$ different evolutionary routes

of BPNe formation. However, the different processes listed above are not completely independent, so the number of routes is much lower. For example, a very high accretion rate requires a close orbit, which in most cases results in strong tidal interaction. The connection between the different parameters and the probability for each route requires a separate study, e.g., a population synthesis. On the other hand, several other factors increase the number of different appearances of bipolar PNe. (1) In many cases a system will move from one type to another. For example, if the AGB wind's mass-loss rate increases and/or its speed decreases in the very last stages of the FIW (superwind) phase, the accretion rate by the companion increases, and a weak CFW may become strong. As a result, the descendant PN will contain an outer structure formed by a weak CFW, and an inner region formed by a strong CFW. The opposite transition occurs when the mass-loss rate decreases during the proto PN phase. (2) Back flow. An accretion by the post-AGB star of material flowing back may lead to a CFW blown by the post-AGB star (Soker 2001b). (3) Orientation. The inclination angle of the symmetry axis of a BPN (or a proto-BPN) influences its apparent morphology as well (e.g., Su, Hrivnak, & Kwok 2001). (4) Thermal pulse. During a thermal pulse (helium flash) the radius and mass-loss rate of the AGB star increase; a short time later they decrease (Blöcker 1995). If a pulse occurs during the FIW it may have an imprint on the descendant PN.

Overall, we estimate that binary progenitors of BPNe can evolve through ~ 100 different evolutionary routes. This number is about equal to the number of well resolved BPNe (and proto-BPNe). Some evolutionary routes are rare, and contain no known PNe; some contain several PNe, but considering the quantitative differences within each evolutionary route, we can safely conclude that *each BPN is a 'unique' object* (as stated above, at present we cannot connect PNe to the exact evolutionary route).

4. SUMMARY

In the present work we strengthened the binary model for the formation of BPNe. In that model the companion influences the mass-loss process mainly during the late AGB phase of the primary mass-loss star, hence the bipolar structure already exists in the post-AGB phase, and the model accounts for proto-BPNe as well. The main goal was to show that in the binary model there are many evolutionary routes to form BPNe, hence every BPN is 'unique', and there is no need to invoke new evolutionary paradigm for each BPN, as some papers have argued in recent years. As a case study, we tried to build a model for the formation of the proto-BPNe OH231.8+4.2, which according to ABSNZ and BCAS is a challenge to existing theories. We argued in section 2 that the binary model can naturally account for its properties. We predicted that most likely the central AGB star of OH231 has a main sequence companion of mass $\sim 1 M_\odot$, orbital period of ~ 5 yr, and eccentricity of $\gtrsim 0.1$. In section 2 we also discussed several other evolutionary routes, extending the list for general cases in section 3. The main qualitative parameters which determine the different

evolutionary routes are listed in the first column of Table 1. Within each evolutionary route there are quantitative differences, which further enrich the variety of descendant PNe morphologies. We noted that some routes, e.g., weak tidal interaction and weak CFW (collimated fast wind) will lead mainly to elliptical PNe rather than BPNe (Soker 2001a).

We request a stop to attaching adjectives such as, 'unique', 'peculiar', and 'unusual' to BPNe and proto-BPNe, since almost every BPNe is 'unique' in the evolutionary route of its progenitor binary star.

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TABLE 1
EVOLUTIONARY ROUTES OF BIPOLAR PN PROGENITORS

Parameter	Possibilities	Symbol	Possible Example	Number of Possibilities
CFW (jets) type	Strong	W1	Hb 12[1]	
	Strong at periastron	W2	Hu 2-1[5]	
	Weak[a]	W3	Egg Nebula[7]	3
Companion	Main Sequence	C1		
	WD: Outburst at FIW phase+ionization[b]	C2	M 2-9[W3][4]	
	WD: No outburst at FIW phase+ionization[c]	C3		
	WD: Steady nuclear burning+ionization[d]	C4		
	WD: Steady nuclear burning+swelling	C5		5
Tidal interaction	Weak[a]	T1		
	Strong (synchronization)	T2	Red Rectangle[W2][6][C1][8]	
	Strong + Roche lobe over flow	T3	OH231.8+4.2[C1][2]	
	Strong + Common envelope [e]	T4	NGC 2346[C1][3]	4
CFW (jets) precession	Precession	P1	He 3-1475[1]	
	No precession	P2	Hen 3-401[1]	2

'FIW' stands for Final Intensive Wind (superwind) at the end of the AGB. 'Outburst' means that there is no steady nuclear burning on the WD surface, but rather a recurrent nuclear outbursts. '[ ]' indicates other parameters of the system according to the symbols in the table.

Comments: (a) Systems with both weak tidal interaction and weak CFW will form mainly elliptical PNe (Soker 2001a). (b) Such systems are symbiotic novae (but not necessarily during the FIW phase). (c) Such systems are symbiotic systems (but not necessarily during the FIW phase). (d) Such systems are supersoft X-ray sources. (e) Beside NGC 2346, all other known close central stars of PNe (Bond 2000), are located inside elliptical PNe, i.e., no lobes are observed.

Sources: (1) Suggestions made here based on HST images; (2) Studied in detail in this paper; (3) Bond & Livio (1990); (4) Livio & Soker (2001); (5) Miranda *et al.* (2001); (6) Soker 2000; (7) SR00; (8) H. Van Winckel 2001, private communication.